RF TRAP TUNED BY SELECTIVELY INSERTING ELECTRICALLY CONDUCTIVE TUNING ELEMENTS

DESCRIPTION

The following relates to the radio frequency arts. It finds particular application in magnetic resonance imaging scanners, and will be described with particular reference thereto. However, it also finds other radio frequency applications.

In magnetic resonance imaging scanners, the radio frequency coil typically is connected with a radio frequency trap to provide common mode high impedance to radio frequency current flow. In one common configuration, the radio frequency trap is a balanced butterfly trap including two dielectric formers or bobbins. A coaxial cable is wrapped around the two dielectric formers to define an inductive element. In the balanced butterfly topology, the cable is wrapped in oppositely directed helices on the two formers to produce oppositely directed magnetic fields in the two formers. The oppositely directed helical wrapping provides external field cancellation which is advantageous since the radio frequency trap is typically disposed relatively close to the radio frequency coil and inside the high magnetic field environment. A capacitance is connected across the shield conductor of the inductive element to form a resonant LC circuit having a resonance frequency:

$$\omega_{res} = \frac{1}{\sqrt{LC}} \qquad (1),$$

where L is the inductance of the inductive element formed by the wrapping of the cable around the dielectric formers, C is the capacitance value, and ω_{res} is the resonant frequency of the radio frequency trap.

One difficulty in constructing radio frequency traps is fine tuning of the resonant frequency ω_{res} to closely match the magnetic resonance frequency. The magnetic resonance frequency is typically in the tens or hundreds of megahertz. For example, at a main B_0 magnetic field of 3.0 Tesla, the resonance frequency is about 128 MHz. Commercial discrete fixed-value capacitors are not readily available with sufficiently narrow tolerances to ensure the trap has the desired resonant frequency without fine tuning of the resonance frequency ω_{res}.

In one approach to fine tuning, different fixed-value capacitors are tested in the butterfly trap. Since the capacitance value varies substantially from capacitor to

capacitor (for example, commercial capacitors have a typical tolerance of about 5%), some capacitors may produce resonance closer to the desired resonance frequency than others. This approach has a number of drawbacks. It necessitates maintaining a large supply of capacitors for testing. Even with a large supply of capacitors, however, the possibility exists that no capacitor on hand will provide the desired resonant frequency. Moreover, a high degree of manual labor is involved in soldering and desoldering capacitors during the fine tuning process.

In another approach, a variable capacitor is used. The variable capacitor is readily adjusted to provide fine tuning. However, high power variable capacitors are large and bulky, which is problematic given the premium placed on space within a magnetic resonance imaging scanner housing and bore. Variable capacitors are also expensive.

In some radio frequency traps, tuning is achieved by adjusting a spacing of the cable windings. However, adjusting the windings is labor intensive and time consuming, and the adjusted windings can break the butterfly trap symmetry and reduce advantageous external field canceling. Moreover, changes in the adjusted winding spacing over time due to vibrations, magnetic forces, or other influences can cause detuning of the radio frequency trap.

The present invention contemplates an improved apparatus and method that overcomes the aforementioned limitations and others.

According to one aspect, a method is provided for tuning a radio frequency trap having an inductive element including a dielectric former and a coaxial cable wrapped around the former. An effective amount of electrically conductive material is inserted into the dielectric former, the amount being effective to adjust an inductance of the inductive element to tune the radio frequency trap to a selected resonant frequency value.

According to another aspect, a radio frequency trap is disclosed, including one or more dielectric formers. At least a portion of a cable including an inner conductor and a coaxial outer conductor is wrapped around the one or more dielectric formers. The coaxial outer conductor of the portion of the cable wrapped around the one or more dielectric formers defines at least one inductive element. A capacitance is connected across the at least one inductive element. A selected amount of electrically conductive material is inserted into the one or more dielectric formers. The selected amount of electrically

conductive material cooperates with the at least one inductive element and the capacitance to define a resonant circuit having a selected resonance frequency.

According to yet another aspect, an apparatus is disclosed, including a radio frequency trap. The radio frequency trap includes an even number of dielectric formers, a coaxial cable wrapped around the dielectric formers, and a plurality of tuning elements selectively inserted into the dielectric formers to tune the radio frequency trap to a selected resonance frequency.

According to still yet another aspect, a radio frequency trap is disclosed. At least a portion of a cable including an inner conductor and a coaxial outer conductor is wrapped around one or more dielectric formers. The coaxial outer conductor of the portion of the cable wrapped around the one or more dielectric formers defines at least one inductive element. A capacitance is connected across the at least one inductive element. One or more electrically conductive fasteners secure the one or more dielectric formers to a substrate. At least a portion of each electrically conductive fastener is disposed inside the dielectric former to which it fastens.

One advantage resides in simplified tuning of a radio frequency trap.

Another advantage resides in reduced cost of a tuned radio frequency trap.

Yet another advantage resides in precise tuning of a radio frequency trap.

Still yet another advantage is fixed positioning of the windings of a butterfly trap which reduces the likelihood of detuning due to changes in spacing of the windings due to vibrational, magnetic, or other influences.

Numerous additional advantages and benefits will become apparent to those of ordinary skill in the art upon reading the following detailed description of the preferred embodiments.

The invention may take form in various components and arrangements of components, and in various process operations and arrangements of process operations. The drawings are only for the purpose of illustrating preferred embodiments and are not to be construed as limiting the invention.

FIGURE 1 shows a diagrammatic representation of a magnetic resonance imaging system including a radio frequency butterfly trap.

FIGURE 2 shows a perspective view of the radio frequency butterfly trap of FIGURE 1.

FIGURE 3 shows a perspective view of one of the bobbins of the radio frequency butterfly trap of FIGURE 2.

FIGURE 4 shows a perspective view of the radio frequency butterfly trap of FIGURE 2 mounted to a board with a printed circuit capacitor disposed on the board.

FIGURE 5 shows a perspective view of a chip capacitor connected to the coaxial cable of the radio frequency butterfly trap of FIGURE 2.

FIGURE 6 shows a perspective view of the radio frequency butterfly trap of FIGURE 2 with one tuning screw inserted into each bobbin, and one non-electrically conductive screw inserted for mechanical fastening.

FIGURE 7 shows a perspective view of the radio frequency butterfly trap of FIGURE 2 with two tuning screws inserted into each bobbin, in which the tuning screws also serve as fasteners for securing the radio frequency butterfly trap to a board.

FIGURE 8 shows a perspective view of another embodiment of the radio frequency butterfly trap, in which tuning rods are employed, mounted to a board. In FIGURE 8, one half of the tuning rods are inserted, while the other half of the tuning rods are shown aligned for insertion into the bobbins.

FIGURE 9 shows a perspective view of one of the bobbins of the radio frequency butterfly trap of FIGURE 8.

With reference to FIGURE 1, a magnetic resonance imaging scanner **10** includes a housing **12** defining a generally cylindrical scanner bore **14** inside of which an associated imaging subject **16** is disposed. Main magnetic field coils **20** are disposed inside the housing **12**, and produce a main B_0 magnetic field directed generally along and parallel to a central axis **22** of the scanner bore **14**. The main magnetic field coils **20** are typically superconducting coils disposed inside cryoshrouding **24**, although resistive main magnets can also be used.

The housing **12** also houses or supports magnetic field gradient coils **30** for selectively producing magnetic field gradients parallel to the central axis **22** of the bore **14**, transverse to the central axis **22**, or along other selected directions. The housing **12** further houses or supports a radio frequency body coil **32** for selectively exciting and/or detecting

magnetic resonances. A coil array **34** disposed inside the bore **14** includes a plurality of coils, specifically four coils in the example coil array **34**, although other numbers of coils can be used. The coil array **34** can be used as a phased array of receivers for parallel imaging, as a sensitivity encoding (SENSE) coil for SENSE imaging, or the like. In one embodiment, the coil array **34** is an array of surface coils disposed close to the imaging subject **16**. The housing **12** typically includes a cosmetic inner liner **36** defining the scanner bore **14**.

The coil array **34** can be used for receiving magnetic resonances that are excited by the whole body coil **32**, or the magnetic resonances can be both excited and received by the coil array **34**. Moreover, it is also contemplated to excite magnetic resonance with the coil array **34** and detect the magnetic resonance with the whole body coil **32**. It will be appreciated that if one of the coils **32**, **34** is used for both transmitting and receiving, then the other one of the coils **32**, **34** is optionally omitted.

The main magnetic field coils **20** produce a main magnetic field B_0. A magnetic resonance imaging controller **40** operates magnetic field gradient controllers **42** to selectively energize the magnetic field gradient coils **30**, and operates a radio frequency transmitter **44** coupled to the radio frequency coil **32** or to the coils array **34** via a radio frequency switch **45** to selectively energize the radio frequency coil or coil array **32**, **34**. By selectively operating the magnetic field gradient coils **30** and the radio frequency coil **32** or coil array **34** magnetic resonance is generated and spatially encoded in at least a portion of a region of interest of the imaging subject **16**. By applying selected magnetic field gradients via the gradient coils **30**, a selected k-space trajectory is traversed, such as a Cartesian trajectory, a plurality of radial trajectories, or a spiral trajectory. Alternatively, imaging data can be acquired as projections along selected magnetic field gradient directions. During a readout phase of imaging data acquisition, the magnetic resonance imaging controller **40** operates the switch **45** to couple a radio frequency receiver **46** to the coils array **34** or the whole body coil **32**, to acquire magnetic resonance samples that are stored in a magnetic resonance data memory **50**.

The imaging data are reconstructed by a reconstruction processor **52** into an image representation. In the case of k-space sampling data, a Fourier transform-based reconstruction algorithm can be employed. Other reconstruction algorithms, such as a filtered backprojection-based reconstruction, can also be used depending upon the format

of the acquired magnetic resonance imaging data. For SENSE imaging data, the reconstruction processor **52** reconstructs folded images from the imaging data acquired by each coil, and then combines the folded images along with coil sensitivity parameters to produce an unfolded reconstructed image.

The reconstructed image generated by the reconstruction processor **52** is stored in an image memory **54**, and can be displayed on a user interface **56**, stored in non-volatile memory, transmitted over a local intranet or the Internet, viewed, stored, manipulated, or so forth. The user interface **56** can also enable a radiologist, technician, or other operator of the magnetic resonance imaging scanner **10** to communicate with the magnetic resonance imaging controller **40** to select, modify, and execute magnetic resonance imaging sequences.

With continuing reference to FIGURE 1 and with further reference to FIGURES 2-7, a butterfly trap or balun **60** (revealed in FIGURE 1 by partial cutaway of the housing **12**) is inserted on the line connecting the radio frequency switch **45** with the coil **32**, **34**. The butterfly trap or balun **60** provides a common mode high impedance to radio frequency current flow. As shown in FIGURE 2, the radio frequency trap **60** includes a pair of generally cylindrical dielectric formers or bobbins **62** around which is wrapped a coaxial cable **64**. The coaxial cable is wrapped around the formers **62** in opposite directions so that when a reference electric current "I" flows in the cable **64** in the direction indicated in FIGURE 2, oppositely directed reference magnetic fields "B" are produced in the two formers **62**. Thus, the portions of the cable **64** wrapped around the dielectric formers **62** define an inductive element **66** comprising two inductors electrically connected in series. The reference electric current "I" and reference magnetic fields "B" show the relative relationship between current and magnetic fields; however, the directions of the electric current and magnetic field switch back-and-forth at radio frequencies.

In one embodiment, each dielectric former or bobbin **62** includes a corkscrew slot or helical groove **70** (best seen in FIGURE 3) formed on the cylindrical surface of the dielectric former **62**. The coaxial cable **64** is received by the corkscrew slot **70** to provide alignment and determine spacing of the coils of the coaxial cable **64** on the dielectric formers **62**. In another embodiment (not illustrated), the corkscrew slot **70** is omitted.

A capacitor **74** is connected across the inductive element **66** to define an LC resonant circuit. More specifically, the capacitor **74** is connected across ends of a shield conductor of the coaxial cable **64**. The capacitor **74** is shown diagrammatically in FIGURE 2 using a capacitor circuit symbol. In one embodiment, the butterfly trap **60** is secured to a printed circuit board **78** (shown in FIGURES 4 and 7), and the capacitor **74** is a chip capacitor (shown in FIGURE 5). Ends of the cable **64** are stripped to form connection ends **80** for connection with the printed circuit board **78**, for connection with cabling of one or both radio frequency coils **32, 34**, or for connection elsewhere in the radio frequency energizing or detection circuitry. While the printed circuit board **78** is illustrated as supporting only the butterfly trap **60**, it is to be appreciated that additional radio frequency circuitry or other electronics can be fabricated on, supported by, and/or interconnected via the printed circuit board **78.**

The butterfly trap **60** has a resonant frequency related to the inductance of the inductive element **66** and the capacitance of the capacitor **74**. For a simple parallel LC resonant circuit topology, the butterfly trap **60** has a resonant frequency ω_{trap} in accordance with Equation (1), that is, $\omega_{trap}=(LC)^{-0.5}$ where L is the inductance of the inductive element **66** and C is the capacitance of the capacitor **74**. It is also contemplated to employ other resonant circuit topologies, for which the resonant frequency may have a different functional dependence upon the inductance of the inductive element or elements.

Typically, the capacitor **74** is a commercial capacitor having a nominal capacitance that generally varies within a specified tolerance. For example, the capacitance may have a 5% tolerance. Similarly, the inductive element **66** formed by winding the coaxial cable **64** on the bobbins **62** has a certain typical tolerance related to factors such as reproducibility of the spacing of the cable windings, reproducibility of the density and shape of the bobbins **62**, and the like. These tolerances in capacitance and inductance lead to a corresponding tolerance of the resonant frequency of the butterfly trap, which tolerance may be too large to ensure precise tuning of the trap respective to the magnetic resonance frequency or other desired resonance frequency.

In order to fine tune the butterfly trap **60** to the magnetic resonance frequency or to another desired radio frequency resonance value, the capacitance is fixed and the inductance of the inductive element **66** is adjusted to achieve the target resonance frequency. The inductance is adjusted with electrically conductive material inserted into

the formers **62**. In the embodiment illustrated in FIGURES 2-7, the electrically conductive material is in the form of electrically conductive fasteners, such as electrically conductive screws **84** (shown in FIGURES 6 and 7) that screw into the formers **62** to secure the formers **62** and hence the butterfly trap **60** to the printed circuit board **78**.

In one embodiment, the radio frequency trap **60** is disposed in the main B_0 magnetic field. In this embodiment, the electrically conductive screws **84** are suitably non-ferromagnetic. Insertion of non-ferromagnetic conductive material into the dielectric formers **62** effectively lowers the inductance of the inductive element **66**. Thus, in accordance with $\omega_{trap}=(LC)^{-0.5}$ the reduced inductance L causes an increase in the butterfly trap resonant frequency ω_{trap}. As more non-ferromagnetic conductive material is inserted into the dielectric formers **62**, the trap resonant frequency ω_{trap} increases. In this embodiment, the capacitance of the capacitor **74** should be selected to be large enough to ensure that the trap resonant frequency is smaller than the desired trap resonant frequency value before insertion of any non-ferromagnetic conductive material into the formers **62**.

In another embodiment, the radio frequency trap **60** is disposed outside of the main B_0 magnetic field. In this embodiment, the electrically conductive screws **84** can be non-ferromagnetic, as before, or they can be ferromagnetic. Insertion of ferromagnetic conductive material into the dielectric formers **62** effectively raises the inductance of the inductive element **66**. Thus, in accordance with $\omega_{trap}=(LC)^{-0.5}$ the increased inductance L causes a reduction in the butterfly trap resonant frequency ω_{trap}. As more ferromagnetic conductive material is inserted into the dielectric formers **62**, the trap resonant frequency ω_{trap} decreases. When ferromagnetic conductive material is used for tuning, the capacitance of the capacitor **74** should be selected to be small enough to ensure that the trap resonant frequency is larger than the desired trap resonant frequency value before insertion of any ferromagnetic conductive material into the formers **62**.

When the butterfly trap **60** is arranged in the main B_0 magnetic field, it is advantageous to have the trap **60** balanced to reduce external magnetic fields. Thus, the number of dielectric formers **62** is preferably even. For example, two formers **62** can be used as illustrated. The coaxial cable **66** is wrapped in oppositely directed helices on the two dielectric formers **62** to produce anti-parallel magnetic fields in the two formers **62**. Moreover, an equal amount of the electrically conductive tuning material is preferably

inserted into each of the two formers **62** to maintain field-balancing in the fine-tuned butterfly trap.

In one embodiment, the bobbins **62** are fastened to the printed circuit board **78** using either electrically conductive screws **84**, or electrically insulating screws **85** (for example, Teflon screws), or some combination of electrically conductive screws **84** and electrically insulating screws **85**. The electrically conductive screws **84** and the electrically insulating screws **85** are mechanically interchangeable.

As shown in FIGURES 6 and 7, each bobbin **62** is secured to the printed circuit board **78** by two screws, which can be two electrically conductive screws **84** as shown in FIGURE 7, or can be two electrically insulating screws, can be two electrically conducting screws of different length, or can be one electrically conductive screw **84** and one electrically insulating screw **85**, as shown in FIGURE 6. By selecting among screws of different length and gauges a large number of corresponding selectable tuning values can be achieved. For example, the screws can vary in length from about a half centimeter to two centimeters. For fine tuning, small amounts can be ground off the end of one of the screws, or one of the screws can be incompletely inserted.

Additional levels of tuning can be provided by using three, four, or more screws for securing each bobbin **62**, and selecting from amongst electrically conductive screws **84** and electrically insulating screws **85** to control the total amount of electrically conductive material inserted into the bobbins **62**. In another contemplated, embodiment, composite screws that have varying amounts of electrically conductive material are used to provide still further levels of fine tuning of the trap resonance frequency.

The embodiment of FIGURES 2-7 has the advantage that the fasteners already used to fasten the radio frequency trap **60** to the printed circuit board **78** are additionally used to selectably fine tune the frequency of the butterfly trap **60**.

With reference to FIGURES 8 and 9, another embodiment of the balanced radio frequency butterfly trap **60'** is illustrated. In FIGURES 8 and 9, components that are unchanged from the trap **60** of FIGURES 2-7 are labeled with the same reference numbers, while modified components are labeled with corresponding primed reference numbers. New components are labeled with new reference numbers.

In the butterfly trap **60'**, the coaxial cable **64** is wrapped around modified dielectric formers or bobbins **62'** to form modified inductive element **66'**. In one

embodiment, the bobbins **62'** are generally cylindrical and each include a helical slot **70'** formed into the cylindrical surface of the bobbin **62'**. The capacitor is suitably the same capacitor **74** as in the trap **60**, and is not shown in FIGURES 8 and 9. The trap **60'** is secured to the printed circuit board **78** using fasteners (not shown) that are either not electrically conductive or which do not insert into the formers **62'**. In another variation, the fasteners are electrically conductive and do insert into the formers **62'**, but are always electrically conductive. In any of these cases, the fasteners are not used for fine tuning the butterfly trap **60'**.

Instead, fine tuning is achieved by selectively inserting electrically conductive rods or dowels **90** into openings **92** formed into the dielectric formers **62'**. In FIGURE 8, three tuning rods **90** are inserted into each bobbin **62'**, while three other tuning rods **90** are shown aligned for insertion into each bobbin **62'**. Advantageously, the rods or dowels **90** can be inserted or removed without partially or entirely unfastening the butterfly trap **60'** from the printed circuit board **78**. Moreover, if less electrically conductive material is needed, then some electrically conductive rods or dowels **90** are omitted, leaving the corresponding openings **92** unfilled. There is generally no need to insert dummy insulating dowels into these openings. Moreover, the number of openings is not tied to the number of mechanical fasteners. As illustrated in FIGURES 8 and 9, a relatively large number of openings **92** can be provided to provide a large number of fine tuning levels for the butterfly trap **60'**.

Analogously to the trap **60** of FIGURES 2-7, the electrically conductive rods or dowels **90** can be non-ferromagnetic or, if the environment is non-magnetic, can be ferromagnetic. Non-ferromagnetic dowels reduce the inductance and increase the resonance frequency, while ferromagnetic dowels increase the inductance and reduce the resonance frequency.

When using either non-ferromagnetic or ferromagnetic electrically conductive material to tune the trap **60, 60'**, the effective amount of electrically conductive material needed for tuning a particular trap to a particular desired resonance frequency can be determined in various ways. The trap resonance can be measured electrically by connecting a suitable radio frequency probe to the connection ends **80** of the trap **60**. Rods **90** can be advanced into the bobbins **62'** until the target resonance frequency is reached.

When the target resonance frequency is reached with one of the rods only partially inserted, the rod is optionally shortened or replaced by a shorter rod accordingly.

Alternatively, if the tolerance of the capacitor **74** is substantially larger than the tolerance of the inductive element **66, 66'**, then the capacitance of the capacitor **74** largely controls the trap resonance frequency. In this case, the effective amount of material can be calibrated with respect to the capacitance of the capacitor **74**, either empirically or by computing the resonance frequency for the specific trap topology and inductance, for example with reference to Equation (1). In yet another approach, the trap **60, 60'** can be tuned after installation in the magnetic resonance scanner **10**, for example by excitation of the radio frequency coil via the trap **60, 60'**. Once tuned, the rods are optionally cemented into place with epoxy or the like.

In the radio frequency trap **60'** of FIGURES 8 and 9, it is contemplated to calibrate then number of tuning rods **90** that need to be inserted into a particular trap to obtain various resonance frequencies. Once this is done, a user can fine tune the trap to different pre-determined frequencies merely by adding, removing, or shortening tuning rods **90**. Thus, for example, the trap can be selectively fine tuned to different magnetic resonance frequencies to accommodate different main B_0 magnetic fields, different proton resonance systems, and the like.

While balanced butterfly radio frequency traps are illustrated, the fine tuning approach is suitably applied to radio frequency traps including a single dielectric former or more than two dielectric formers. Moreover, a helical cable alignment slot similar to the helical slots **70, 70'** can be included on each former in traps employing a single former or more than two formers. Other electrically conductive tuning elements besides the illustrated fastening screws **84** or rods **90** can be inserted into the bobbins to provide fine tuning in accordance with the fine tuning processed disclosed herein.

If the trap is being used outside of a magnetic environment, then it may be acceptable to use an unbalanced trap. For example, a trap topology other than the butterfly topology can be employed in such cases. Moreover, if the trap is being used outside of a magnetic environment, then a combination of ferromagnetic conductive material and non-ferromagnetic conductive material can be inserted into the bobbin or bobbins to selectively reduce or increase the radio frequency trap resonance frequency.

Furthermore, while the embodiments are described with reference to a magnetic resonance imaging system, it will be appreciated that the radio frequency traps and trap tuning processes disclosed herein are generally applicable to other applications employing radio frequency excitations and signals.

The invention has been described with reference to the preferred embodiments. Obviously, modifications and alterations will occur to others upon reading and understanding the preceding detailed description. It is intended that the invention be construed as including all such modifications and alterations insofar as they come within the scope of the appended claims or the equivalents thereof.